

University of Montana

## ScholarWorks at University of Montana

---

Graduate Student Theses, Dissertations, &  
Professional Papers

Graduate School

---

1984

### Geology and differentiation of Round Butte laccolith central Montana

Alan Robert Liptak  
*The University of Montana*

Follow this and additional works at: <https://scholarworks.umt.edu/etd>

**Let us know how access to this document benefits you.**

---

#### Recommended Citation

Liptak, Alan Robert, "Geology and differentiation of Round Butte laccolith central Montana" (1984).  
*Graduate Student Theses, Dissertations, & Professional Papers*. 7436.  
<https://scholarworks.umt.edu/etd/7436>

This Thesis is brought to you for free and open access by the Graduate School at ScholarWorks at University of Montana. It has been accepted for inclusion in Graduate Student Theses, Dissertations, & Professional Papers by an authorized administrator of ScholarWorks at University of Montana. For more information, please contact [scholarworks@mso.umt.edu](mailto:scholarworks@mso.umt.edu).

COPYRIGHT ACT OF 1976

THIS IS AN UNPUBLISHED MANUSCRIPT IN WHICH COPYRIGHT SUBSISTS. ANY FURTHER REPRINTING OF ITS CONTENTS MUST BE APPROVED BY THE AUTHOR.

MANSFIELD LIBRARY  
UNIVERSITY OF MONTANA  
DATE: 1984



GEOLOGY AND DIFFERENTIATION OF  
ROUND BUTTE LACCOLITH, CENTRAL MONTANA

By

Alan Robert Liptak

B.A., State University of New York, Potsdam, 1982

Presented in partial fulfillment of the requirements for the degree of  
Master of Science  
University of Montana  
1984

Approved by:

Donald W. Hyndman  
Chairman, Board of Examiners

RC Murray  
Dean, Graduate School

June 1, 1984  
Date

UMI Number: EP38237

All rights reserved

INFORMATION TO ALL USERS

The quality of this reproduction is dependent upon the quality of the copy submitted.

In the unlikely event that the author did not send a complete manuscript and there are missing pages, these will be noted. Also, if material had to be removed, a note will indicate the deletion.



UMI EP38237

Published by ProQuest LLC (2013). Copyright in the Dissertation held by the Author.

Microform Edition © ProQuest LLC.

All rights reserved. This work is protected against unauthorized copying under Title 17, United States Code



ProQuest LLC.  
789 East Eisenhower Parkway  
P.O. Box 1346  
Ann Arbor, MI 48106 - 1346

Liptak, Alan R., M.S., June 1984

Geology

Geology and Differentiation of Round Butte Laccolith, Central Montana (49 pages)

Director--Dr. Donald W. Hyndman *DW H*

Round Butte is a differentiated alkalic laccolith on the eastern flank of the Highwood Mountains in west-central Montana. It consists of basal shonkinite overlain by a syenite wedge, capped by a small lens of upper shonkinite chill-zone. Coarse-grained syenite with some pegmatite exists between the lower shonkinite and syenite.

A combination of field, hand sample, thin section, and chemical data point toward liquid immiscibility as the dominant mechanism of differentiation in Round Butte. In addition, crystal settling might have acted on a small scale in the shonkinite and on a larger scale in the syenite. Reexamination of the coarse syenite "transition rock" (Hurlbut and Griggs, 1939) results in a new interpretation as the basal member of the syenite, perhaps formed due to crystal settling onto solid shonkinite. Comparison of other Highwood laccoliths with Round Butte indicates that all are derived from the same parent magma originating in the eastern Highwood Mountains and that the "transition zone" present in the Shonkin Sag laccolith probably formed in a manner similar to the lower syenite on Round Butte.

## ACKNOWLEDGEMENTS

The efforts of many people were combined to make this project a success. I would like to thank Drs. Donald Hyndman and Dave Alt for their frequent advice. Dr. Wayne VanMeter provided helpful comments about the chemistry chapter. Steve Balogh made short work of many thin-sections. John Cuplin's advice on aspects of photography and drafting was invaluable.

Mr. and Mrs. Leroy Strand of Geyser, Montana, allowed access to Round Butte, for which I am grateful. The Turrecks of Coffee Creek, Montana, provided a place to stay and lots of friendly advice during fieldwork at Round Butte.

I want to thank my parents, Ronald and Gloria Liptak, for their undying moral and financial support. I especially want to thank my wife, Ellen, for typing the thesis and for providing technical advice during the long process of transforming rough drafts into finished copies.

## TABLE OF CONTENTS

<u>TITLE</u>	<u>PAGE</u>
Abstract . . . . .	ii
Acknowledgements . . . . .	iii
Introduction . . . . .	1
Structure of the Laccolith . . . . .	8
General . . . . .	8
Dikes . . . . .	10
The Lower Shonkinite . . . . .	11
The Syenite . . . . .	12
Upper Shonkinite . . . . .	17
Petrology and Petrography of Round Butte Laccolith . . . . .	18
Lowest Shonkinite . . . . .	18
Upper Lower Shonkinite . . . . .	23
Lower Syenite . . . . .	24
Upper Syenite . . . . .	28
Upper Shonkinite . . . . .	29
Dikes . . . . .	30
Chemistry of Round Butte Laccolith . . . . .	32
Conclusion . . . . .	45
Bibliography . . . . .	47



## FIGURES AND TABLES

<u>NUMBER</u>	<u>TITLE</u>	<u>PAGE</u>
Figure 1	Sketch	1
Figures 2A, 2B	Maps	3
Figure 3	Geologic Map	4
Figure 4	Cross-section	5
Figure 5	Geologic Map	9
Figures 6A, 6B	Photographs	13
Figures 7A, 7B	Photographs	14
Figure 8	Thin-section Sketch	20
Figure 9	Binary Phase Diagram	22
Figure 10	Ternary Diagram	38
Figure 11	Ternary Diagram	43
Table 1	Rock Units	19
Table 2	Description of Analyzed Samples	32
Table 3	Chemical Data	33

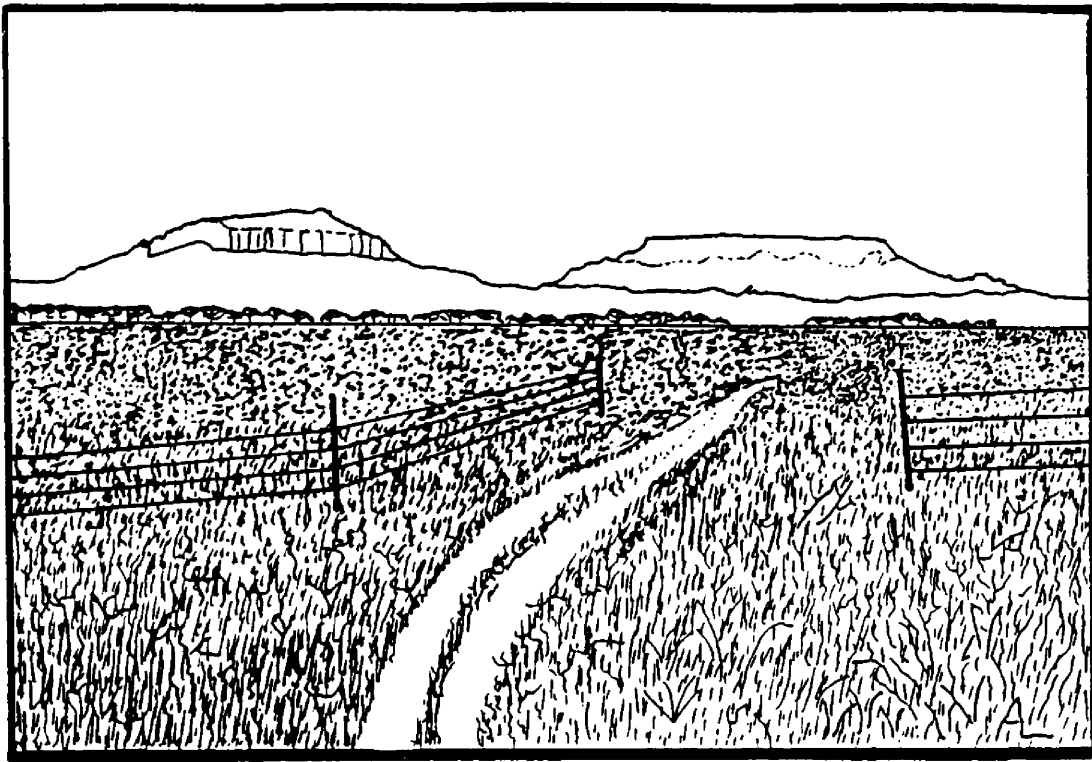


Figure 1 -- Round Butte, left, and Square Butte.  
Looking northeast from Geyser-Geraldine road.

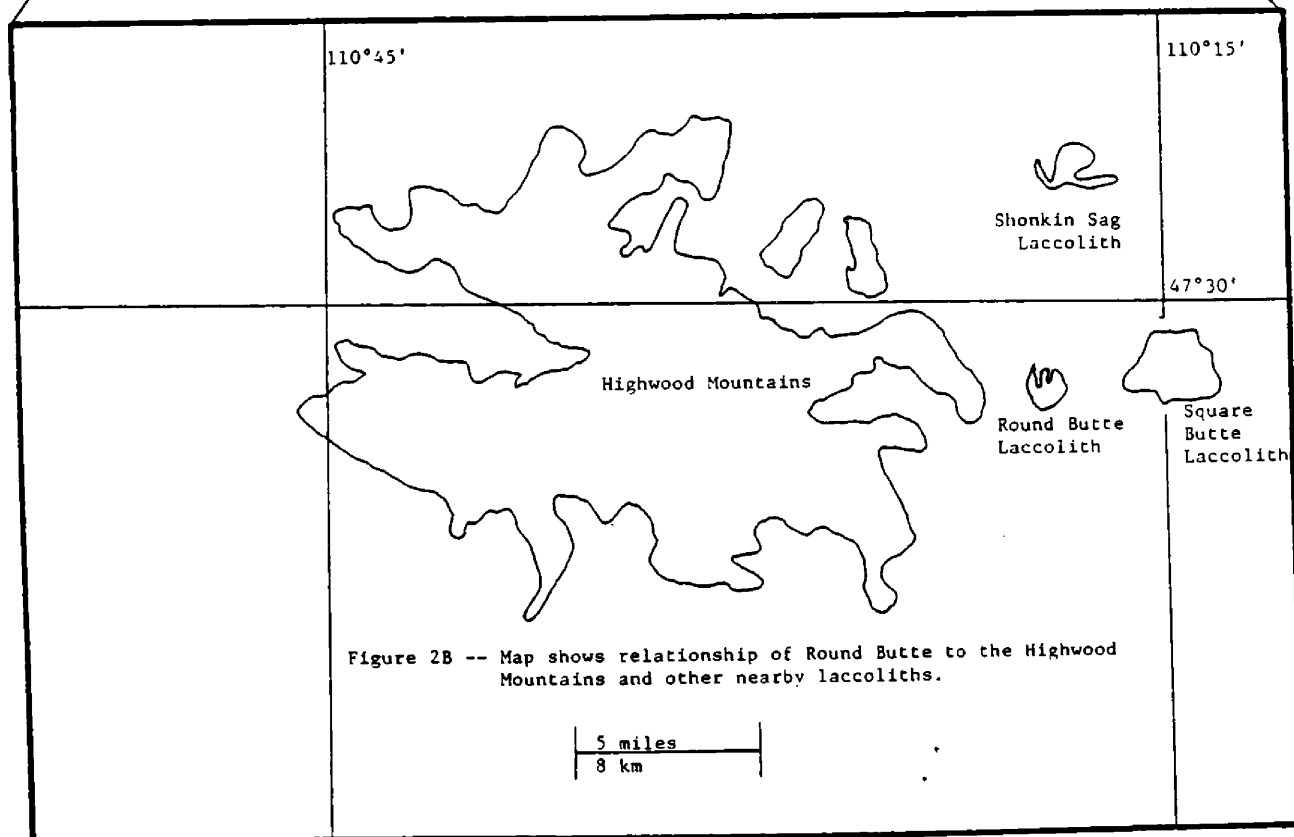
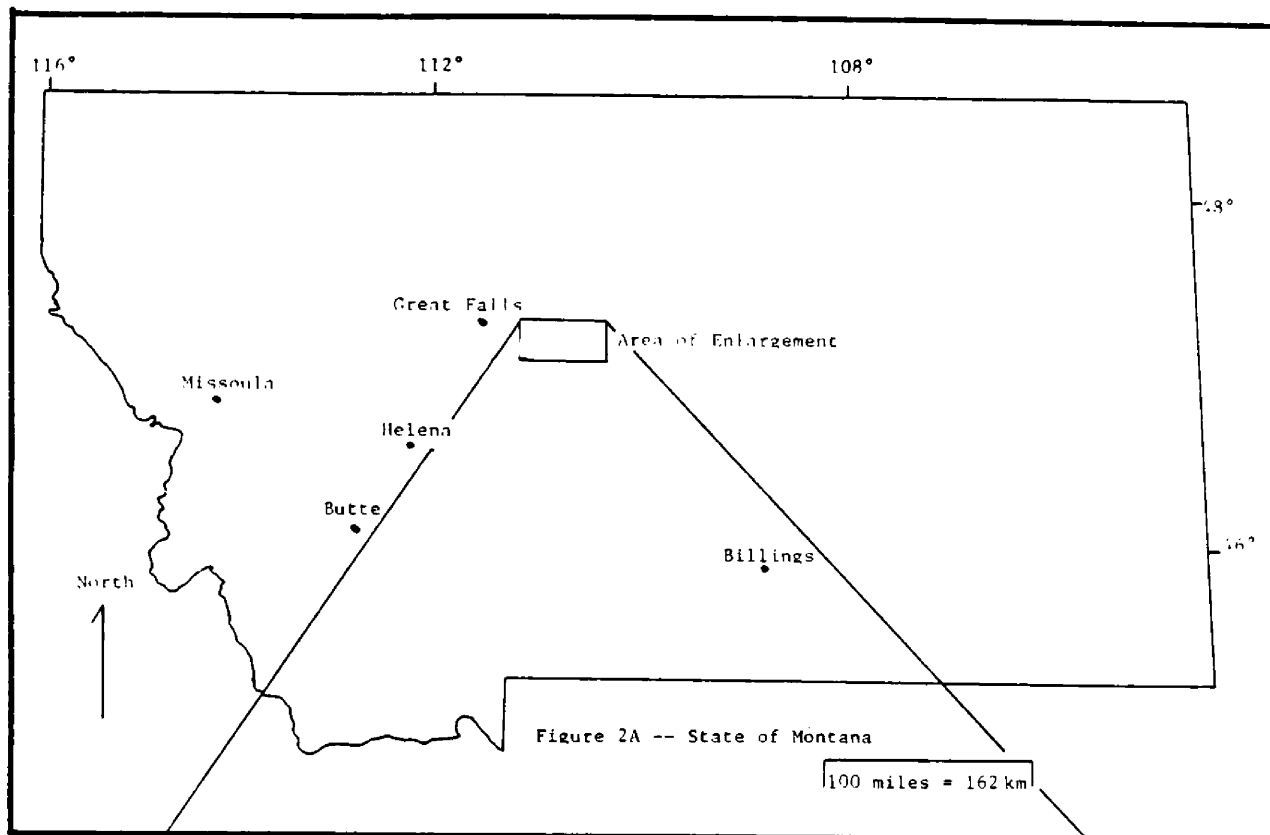
## Introduction

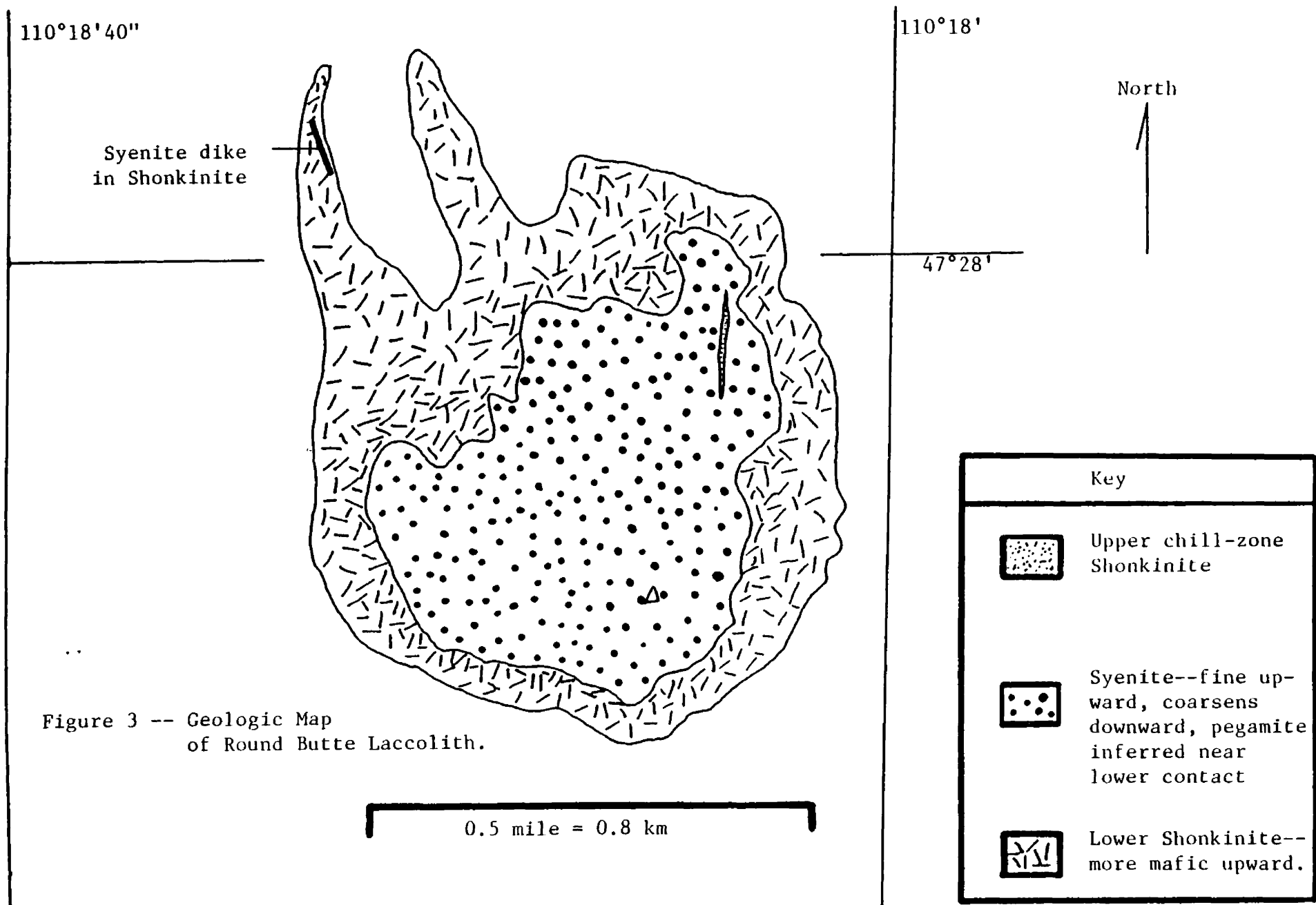
Round Butte is a small laccolith, part of the Montana Alkalic Province of Pirsson (1905) and Larsen (1941). It is on the eastern fringe of the Highwood Mountains, approximately 60 miles east of Great Falls, Montana, six miles south of Shonkin Sag laccolith, and two miles west of Square Butte laccolith (Figures 1 and 2).

Round Butte has differentiated into two dominant rock types. Mafic shonkinite forms dark columnar-jointed cliffs at the base of the laccolith. Felsic syenite overlies the shonkinite. It forms white cliffs high on the laccolith and underlies most of the grassy break between the shonkinite and syenite cliffs. A small shonkinite body above the syenite is the remnant of a once-continuous chill zone (Figures 3 and 4).

Weed and Pirsson (1895) provide the earliest geological information of Round Butte. Their work includes an accurate description of the major units of the laccolith and a chemical analysis of the syenite. A hiatus of 40 years separates their work from the next investigation. Hurlbut and Griggs (1939) surveyed Round Butte as part of a comprehensive study of the laccoliths of the Highwood Mountains. They worked in the northern valleys of the butte and examined features that eluded Weed and Pirsson. They noted an upward density increase in the shonkinite and discovered a coarse "transition zone" low in the syenite cap similar to that in the Shonkin Sag laccolith.

Other laccoliths in the Highwood Mountain region also contain shonkinite overlain by syenite. Differentiation in these laccoliths has





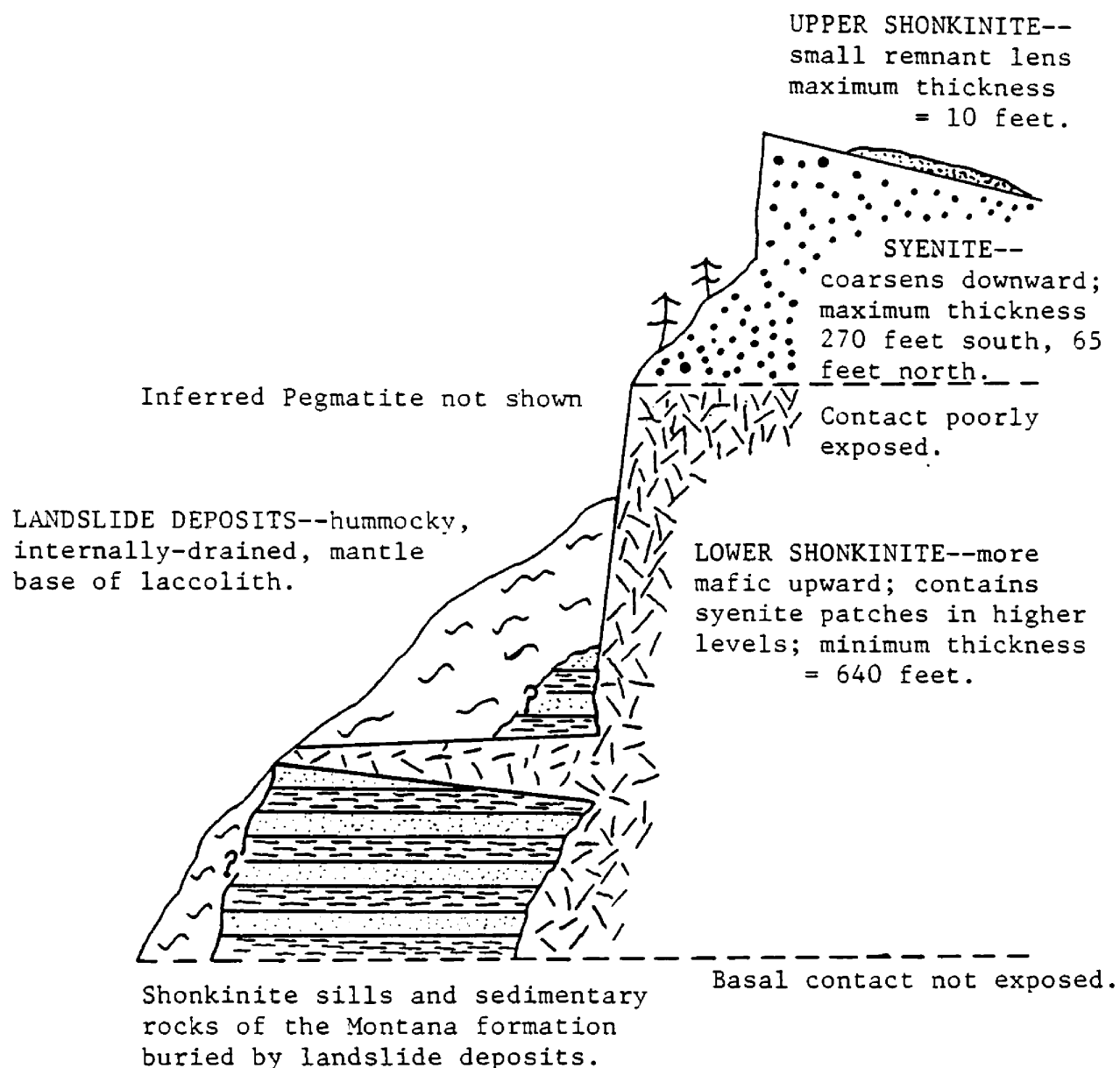


Figure 4 -- Diagrammatic cross-section of Round Butte laccolith. Vertical Scale -- 1 inch = 200 feet = 61.5 meters. Looking westward across south edge of laccolith.

been variously attributed to crystal settling (Hurlbut and Griggs, 1939; Barksdale, 1952), multiple intrusion (Barksdale, 1939), and crystal fractionation modified by diffusion of ionic species (Pirsson, 1905). Pirsson (1905) mentioned "liquation," or liquid immiscibility in reference to differentiation on Square Butte, and observed that crystal fractionation and separation of immiscible magmas are compatible. However, he did not pursue the point, and finally settled on a complex scenerio of crystal fractionation. Later workers dropped the idea of liquid immiscibility probably in deference to Bowen's (1928) rejection.

Re-examination of the Square Butte and Shonkin Sag laccoliths in light of recent experimental and field studies of liquid immiscibility has led to new interpretations. Kendrick and Edmond (1980) decided that liquid immiscibility was the means of differentiation in the Shonkin Sag and Square Butte laccoliths. They noted the absence of positive evidence of crystal settling, such as rhythmic layering, upward density decreases in the rock, and a gentle gradation from mafic to felsic rock. They did find syenitic segregations within the shonkinite, abrupt transitions from mafic to felsic rock, and chemical data supporting liquid immiscibility as the mechanism of differentiation.

I decided to re-examine Round Butte laccolith in light of recent discoveries about magmatic immiscibility. Until now, no complete study of Round Butte laccolith has been made. My objective is to provide a complete geologic report of Round Butte and to propose a model for its differentiation. Field work was completed during the summer of 1983, with laboratory studies of the rocks continuing into the spring of 1984.

Field work and lab studies were supported by grants from the Society of<sup>7</sup>  
Sigma Xi and the Montana Power Company. Chemical analyses were funded  
through a University of Montana grant to D.W. Hyndman.



## STRUCTURE OF THE LACCOLITH

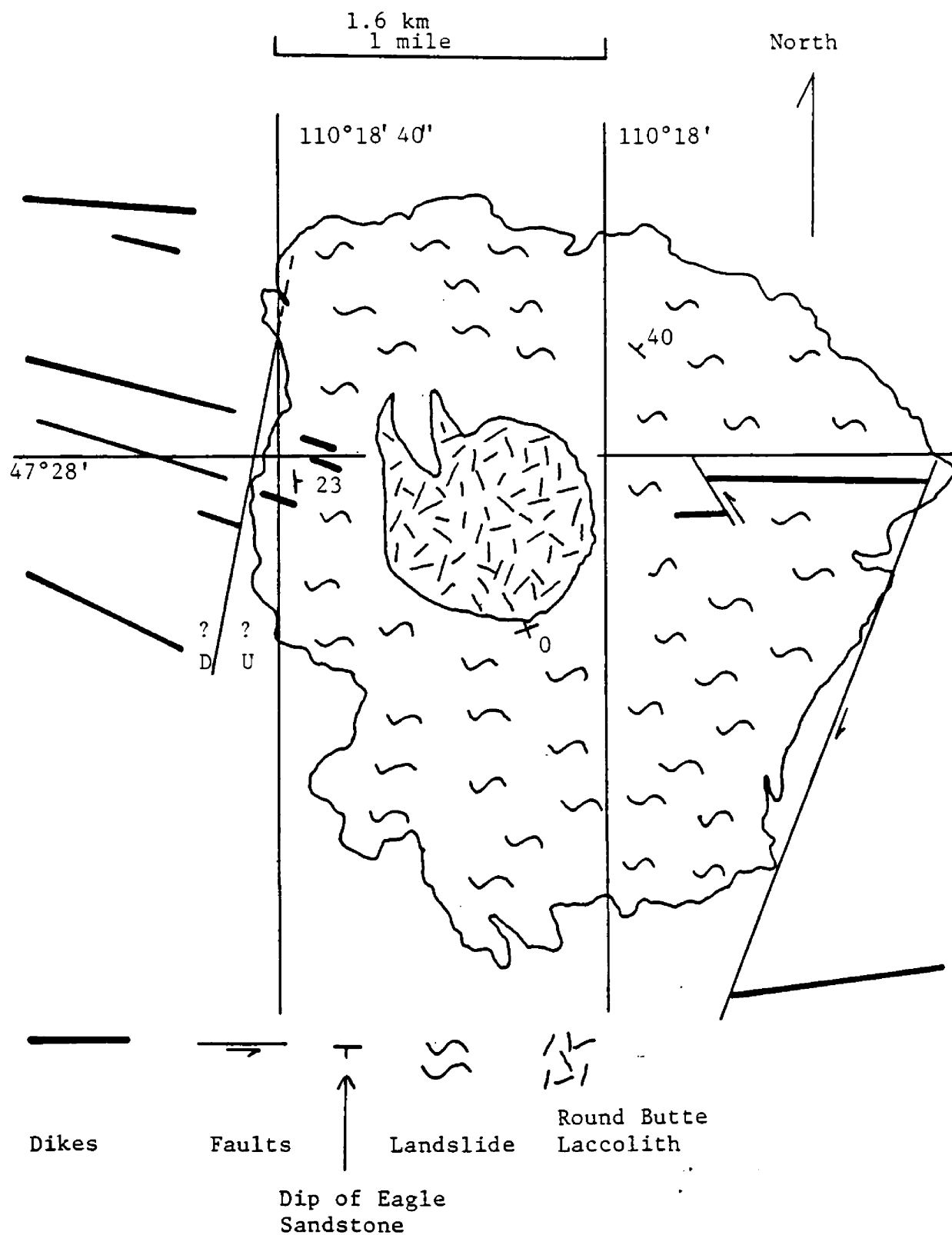
### General

From the north or south, Round Butte laccolith looks like a large bulge beside Square Butte on the high plains east of the Highwood Mountains. It is intruded into the Cretaceous Eagle sandstone, and is partially buried in approximately 200 meters of its own internally-drained landslide debris. Sedimentary rocks are locally exposed among these landslide deposits, along with some shonkinite sills. Outcrops of Eagle sandstone near Round Butte show variable attitude (Figure 5). It is not clear whether the deformation reflects emplacement of the laccolith or landsliding, nor is it clear that these sedimentary rocks are in-situ.

Faults east and west of the laccolith probably moved during emplacement of magma (Figure 5). Sills form when magma intrudes sedimentary rocks concordantly. Some sills expand into laccoliths by raising, arching, and breaking overlying strata. West of Round Butte, a fault truncates dikes and directs stream flow perpendicular to the regional dike trend. The exact movement is uncertain, but I suspect a large vertical component and a smaller horizontal component.

In the Little Belt Mountains, Witkind (1965) found normal faults dipping  $50^{\circ}$  away from laccoliths. These faults reflect deformation that accompanied laccolith emplacement and seem to influence the shape of the developing intrusions. A semi-circular "trap door fault" formed along the southern circumference of Round Butte during the expansion of the laccolith. As the fault moved, liquid syenite filled the wedged-shaped

Figure 5 -- Geologic Map of the Area Surrounding Round Butte Laccolith.



space created. Faults of this type are common in the Judith Mountains (Wallace, 1953).

A left-lateral strike-slip fault with about 150 meters (500 feet) of horizontal motion cuts a dike near the base of the laccolith at its eastern side. The fault trends N 30° W and the dike trends east-west. A larger right-lateral strike-slip fault cuts the same dike one kilometer to the east of the small offset. The fault trends N 20° E and has 2.4 kilometers of strike-slip motion (See Figure 5). The resultant of these two faults pushes a triangular-shaped area east of Round Butte to the north. This may be related to east-west compression, or perhaps it produced vertical movement to create space when magma intruded.

#### Dikes

Several west-northwest/east-southeast trending vertical dikes outcrop west of Round Butte. They are part of the radial swarm originating in the eastern Highwood Mountains. The dikes are variously faulted and rotated and all abruptly end on a north-south fault line tangent to the west side of Round Butte. All the dikes are shonkinite, with augite phenocrysts in a fine-grained groundmass of augite and zeolitized K-feldspar. Leucite appears locally (Buie, 1939). Only one mafic shonkinite dike extends east of Round Butte. This dike crosses a fault, then abruptly "flips" over to the north to form a series of thin shonkinite sills south of Square Butte. It is unclear whether this dike represents the feeder dike for the Square Butte laccolith (D. Hyndman, Personal Communication, 1983). If this dike formed as a splay off of Round Butte, west-to-east flow in the dike is probable.

Hyndman and Alt (1983) performed small-scale gelatin experiments simulating conditions of volcanic emplacement and related intrusion of dikes and laccoliths. These experiments indicate that dikes originating from an experimental volcanic center radiate outward and commonly "flip"  $90^{\circ}$  to form sills. The feeders were usually tangent to the sill. Several good examples of tangential feeder dikes exist in the Adel Mountains southwest of Great Falls; for example, Fort Shaw Butte. By analogy with this experimental system, the feeder dike for Round Butte laccolith may be found tangential to its edge. One such shonkinite dike, somewhat thicker than the other nearby dikes, exists at Round Butte. It is tangent to the thick south side of the laccolith, consistent with intrusion from this direction.

#### The Lower Shonkinite

The lower shonkinite of Round Butte laccolith is its thickest unit. No basal contact is exposed. The lowest exposures occur in valleys on the north side of the laccolith at 1,340 meters (4,360 feet) (Figure 3). The maximum elevation at which the lower shonkinite is seen is between 1,540 and 1,570 meters (5,000 and 5,100 feet), so the minimum thickness of the lower shonkinite is between 200 and 230 meters (640 and 740 feet). Elevation of the lowest exposed shonkinite increases southward to between 1,445 and 1,480 meters (4,700 and 4,800 feet) west, south, and east of the laccolith, where landslide deposits mantle the base of the butte.

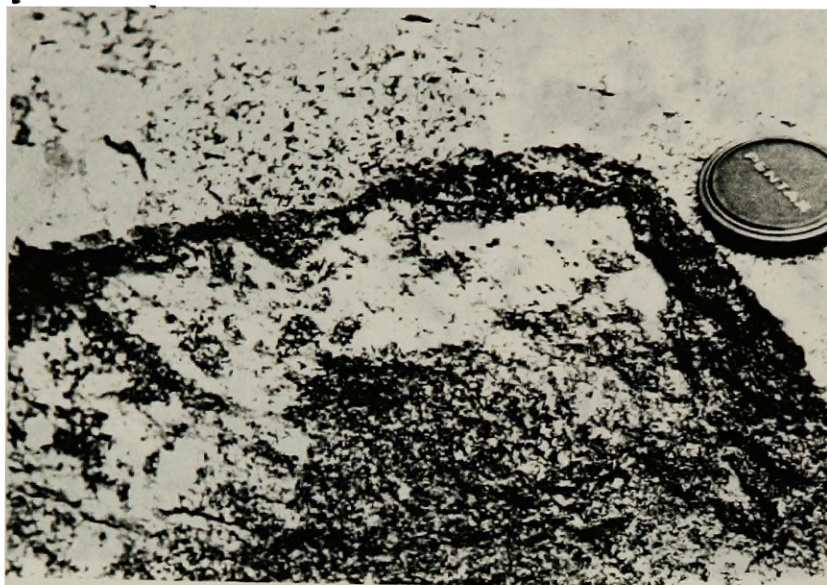
At low elevation, the lower shonkinite is homogeneous. Upward the

rock becomes darker and small patches of fine-grained felsic material appear (Figures 6A and 6B). These are first seen at 1,445 meters (4,700 feet). Higher in the lower shonkinite, felsic segregations become less numerous and larger. Patches up to one meter across occur near the top of the lower shonkinite on the east side of the laccolith (Figures 7A and 7B). These segregations assume several shapes, including elliptical swirls, concave dish structures, pipes, veinlets, and several others that elude brief description. They consist of fine- to medium-grained syenite enclosed in shonkinite. No preferred crystallization sites exist; crystals are randomly distributed throughout the patches. No selvages exist around the syenite, and the mafic crystals around the patches are randomly oriented. The patches may be immiscible separations of syenite that were trapped when the shonkinite crystallized. Disseminated crystallization sites within these patches are consistent with Phillips' (1973) view that interfaces between immiscible liquids are high-energy sites where crystals will not nucleate. Upward increase in size and decrease in number of these patches probably reflects coalescence of many small segregations to form a few larger masses before the shonkinite crystallized.

A porphyritic syenite dike cuts the lower shonkinite on the northwest side of the laccolith (Figure 3). It trends N 20° W and may be a splay off the lower syenite. This dike indicates that the shonkinite finished crystallizing earlier than the syenite.

### The Syenite

A large wedge-shaped body of felsic syenite overlies the lower



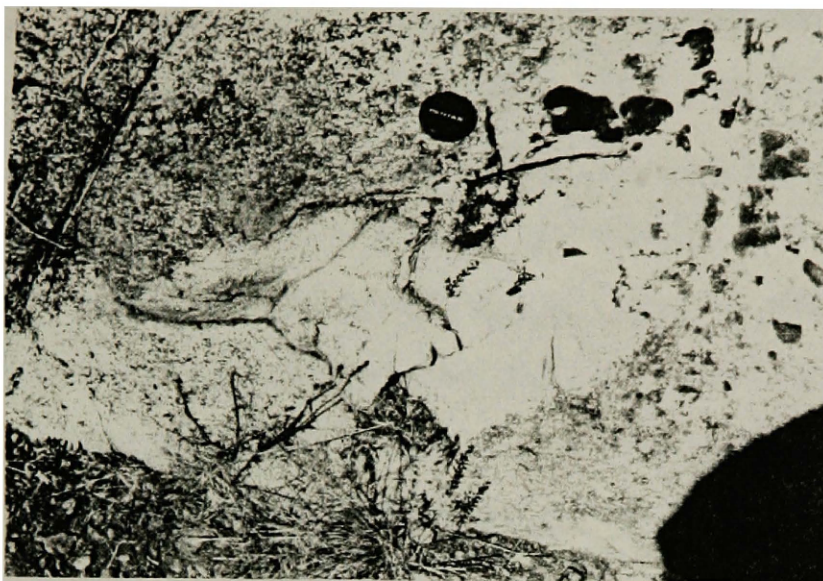
(A)



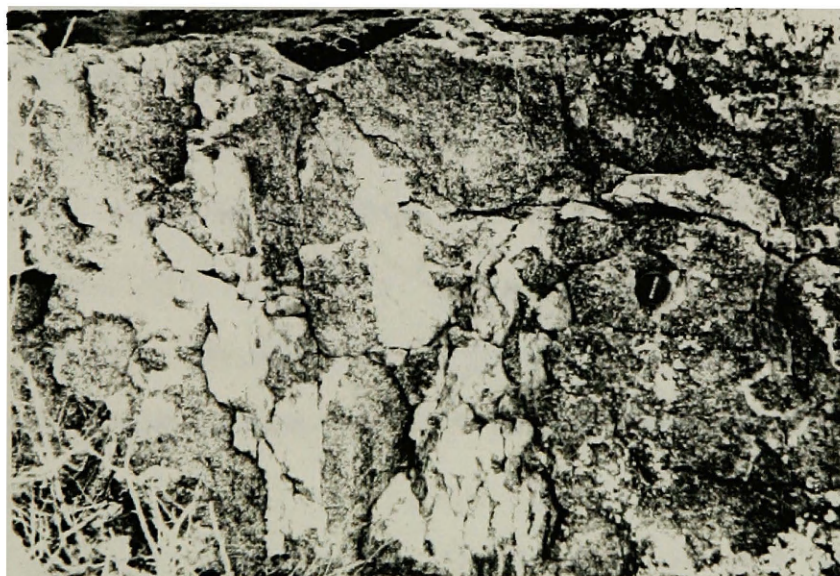
(B)

Figures 6A and 6B -- Small syenite segregations in shonkinite on Round Butte laccolith. (A) is from 1,465 meters (4,760 feet) on west side of Butte; (B) is from 1,460 meters (4,740 feet) central ridge of Butte. Lens cap is 5 centimeters in diameter.





(A)



(B)

Figures 7A and 7B -- Larger syenite patches in shonkinite on Round Butte laccolith. (A) is from 1,505 meters (4,900 feet) on east side of laccolith; (B) is from 1,500 meters (4,880 feet) on ridge on north side of laccolith. Lens cap is 5 centimeters in diameter.

shonkinite. It contains a coarse-grained, porphyritic basal unit and a medium-grained less porphyritic upper unit. Syenite pegmatite exists within the lower part of the syenite. The coarse lower syenite and pegmatite weather easily, so exposure is poor. The unit is exposed at only a half-dozen places on the laccolith. A similar unit on the Shonkin Sag laccolith also weathers easily. Chunks of coarse syenite or pegmatite locally appear in the talus that covers the grass and tree covered break high on Round Butte laccolith. This suggests that Round Butte laccolith is structurally similar to the Shonkin Sag laccolith (Hurlbut and Griggs, 1939; Edmond, 1980) despite form and thickness like the Square Butte laccolith (Kendrick, 1980).

The coarse lower syenite on Round Butte is about 45 meters thick to the south and thins to about ten to twenty meters northward. The upper syenite cliff is 40 meters thick on the south and pinches out northward. On the laccolith's eastern side, an upper shonkinite chill zone directly overlies the lower syenite and the upper syenite is absent. Thus, the wedge shape is a primary igneous feature, not simply erosional.

The contact between the lower syenite and upper chill zone shonkinite is fairly sharp. Mafic minerals of the shonkinite disappear within one centimeter or so and those of the lower syenite appear. The felsic groundmass continues across the boundary, becoming more abundant in the lower syenite. The effect is like that produced by an invisible mesh parallel to the contact, gently undulating on the scale of a centimeter or so, coarse enough to allow free passage of the felsic



materials but too fine to let the mafic phenocrysts through. This situation is more compatible with a two-liquid equilibrium than with an intrusive relationship because the groundmass minerals are continuous across the contact.

The lower shonkinite-syenite contact is very poorly exposed. On the south side of the laccolith at the top of the lower cliffs sub-equal quantities of patchy coarse syenite and shonkinite are present. Hurlbut and Griggs (1939) observed a similar contact between shonkinite and lower syenite on the north side of the laccolith. The pegmatite is coarse, variable rock best seen in talus, composed of augite phenocrysts and graphic intergrowths of augite and zeolite. Relationships between pegmatite and the syenite are uncertain. In the Shonkin Sag laccolith, the pegmatite undulates within the coarse lower syenite (Hurlbut and Griggs, 1939; Barksdale, 1939; Edmond, 1980). A similar situation may exist on Round Butte laccolith.

The upper syenite is a rather homogeneous unit. It is light colored, chalky, with a scattering of mafic minerals giving a "salt and pepper" appearance. In the field the rock locally appears darker due to changes in groundmass color, not increased mafic mineral content. Syenite locally contains miarolitic cavities lined with tiny feldspar crystals. This limits the depth of emplacement to less than three kilometers (Hyndman, 1983, page 151). Very fine-grained segregations of felsic material occur in the syenite. These are pipe-like, two to eight centimeters wide and generally less than 60 centimeters (24 inches) long. They probably are a late differentiation product. The syenite is

horizontally jointed, probably due to unloading.

#### Upper Shonkinite

The upper shonkinite of Round Butte is a small lens on the eastern side of the laccolith. It is the remnant of a once-larger chill zone that enveloped the laccolith. Erosion has removed the rest of the chill zone above the topographically highest parts of the syenite. The upper shonkinite is mineralogically and texturally similar to the lower shonkinite. It overlies fine syenite on the laccolith's eastern side as a small lens one to three meters thick. The contact plunges gently northward, consistent with the wedge shape of the syenite. Farther north, upper shonkinite directly overlies the pegmatite.

### Petrography and Petrology of Round Butte Laccolith

It is useful for petrologic and petrographic description to divide Round Butte laccolith into six separate units. They are, in upward order, the lowest shonkinite, the upper lower shonkinite, the pegmatite and lower syenite, the upper syenite, and the upper shonkinite (Table 1).

### Petrology and Petrography of the Lowest Shonkinite

In hand sample, lowest shonkinite is medium gray, fresh, nearly unaltered porphyritic rock with two to three millimeter augite phenocrysts, plus biotite, orange-brown olivine, magnetite, K-feldspar and zeolite. Phenocrysts show sub-parallel orientation.

Thin sections reveal 33% augite, 45% zeolite, and 5% each of olivine, K-feldspar and biotite, plus minor apatite, magnetite, glass, and possibly analcime. Augite is euhedral, light green with well-developed concentric zoning. Zeolite forms felty low negative relief patches. It is biaxial positive with a small axial angle and appears to be natrolite (Larsen, 1941). Olivine is very slightly altered to iddingsite and serpentine. K-feldspar is fairly abundant in the groundmass and as phenocrysts up to three millimeters across (Figure 8). Biotite grains are pleochroic, varying from cream to dark red-brown color. This may indicate titanium-rich biotite (Troeger, 1979, page 102). Magnetite occurs as scattered octahedra and apatite grains are tiny hexagonal prisms, primarily within augite.

Augite phenocrysts are embayed, with K-feldspar and biotite filling. Augite that grew slowly at mantle depths may be unstable in

TABLE 1 -- SUMMARY OF CHARACTERISTICS OF ROCK UNITS ON ROUND BUTTE LACCOLITH.

UNITS	MAJOR CHARACTERISTICS
Upper Shonkinite	Remnant of chilled envelope; porphyritic, medium-grained, 35% mafic minerals; contains augite, olivine, biotite, K-feldspar, zeolite; overlies syenite south, coarse pegmatite syenite north.
Upper Syenite	Wedge-shaped body, tapers northward; light-colored, equigranular, contains K-feldspar, zeolite, minor augite, aegirine-augite, biotite.
Lower Syenite	Very poorly exposed, appears wedge-shaped, tapers northward; porphyritic, contains 10% augite phenocrysts, graphic intergrowths of augite and zeolite; abundant K-feldspar.
Pegmatite	Unexposed, found in talus; probably an undulating sub-unit of the lower syenite; coarse radial aggregates of augite phenocrysts, large biotite phenocrysts, K-feldspar and zeolites.
Upper Lower Shonkinite	Well-exposed; porphyritic, contains 55% mafic minerals; augite phenocrysts, olivine and biotite with lesser magnetite, K-feldspar and zeolite; more heavily altered than lowest shonkinite; contains syenite segregations.
Lowest Shonkinite	Poorly exposed north of laccolith, unexposed elsewhere; homogeneous, contains 45% mafic minerals; mineralogy similar to upper lower shonkinite; less altered than upper lower shonkinite.



Figure 8 -- Thin-section of shonkinite-syenite contact (arrows). Shonkinite is in lower right, syenite in upper left. See text for details. X21, cross-polarized light. Width of view - 6 mm.

rapidly-crystallizing magma at near-surface pressures. Resorption of augite may reflect time spent in a rising, water-undersaturated magma with decreasing pressure. Augite contains apatite, magnetite and olivine grains of varying size. Olivine contains grains of magnetite. Biotite flakes enclose all other mafic materials.

The inferred order of crystallization is early apatite and olivine, followed by pyroxene and magnetite. As these are all large phenocrysts or are enclosed in phenocrysts, I think these minerals crystallized at depth. During and following intrusion, biotite crystallized. K-feldspar formed late and may have grown as the temperature decreased and the melt travelled down a liquid-solid phase boundary toward an eutectic point (Figure 9). This explains the presence of both phenocrysts and fine acicular K-feldspar. Eutectic crystallization of the fine acicular groundmass and zeolitization of the felsic phases followed.

Augite locally contains altered grains of olivine. This may suggest that alteration of the olivine occurred before its incorporation into the augite during crystallization. More likely, alteration may have followed incorporation if water migrated through cracks in augite crystals.

The rock texture is not cumulate, as is expected in rocks produced by crystal settling. Instead, areas of mafic mineral concentration are separated by patches of K-feldspar and zeolite. Mafic minerals everywhere occur together, no where isolated. If mineral distribution patterns in this rock were random, we would expect to locally find isolated mafic minerals in the felsic domains. The existence of well-

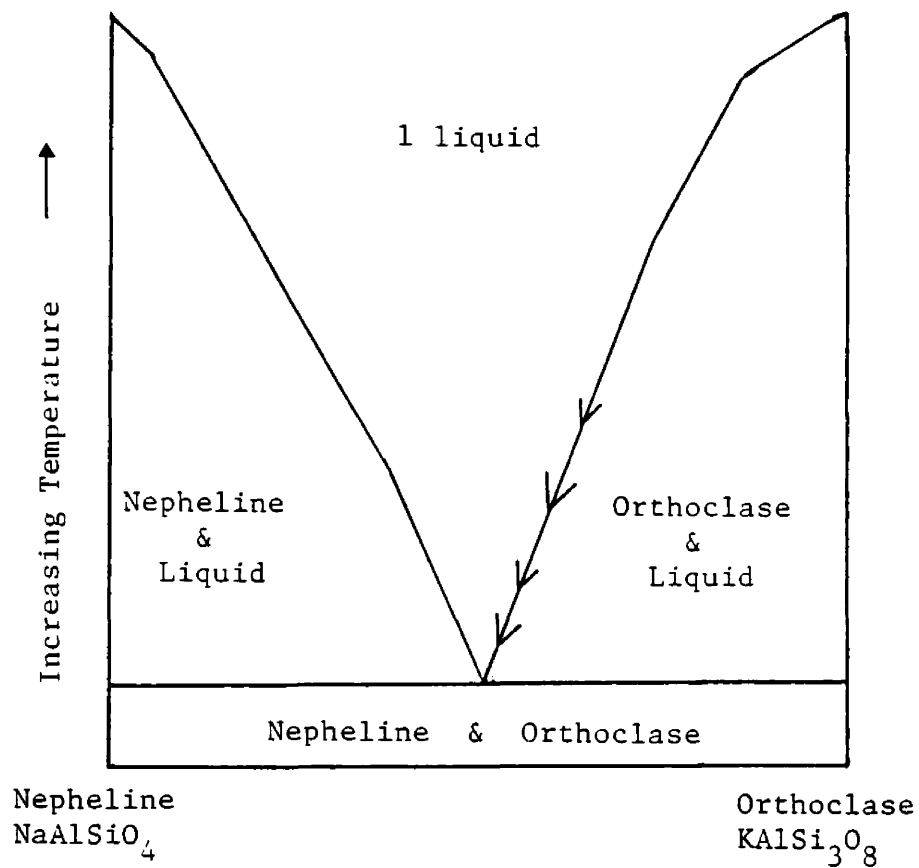


Figure 9 -- Binary phase diagram for the system Nepheline-Orthoclase. Felsic magma at Round Butte may have moved down orthoclase liquidus (arrows) toward an eutectic point. See text for details. Modified from Morse (1980, page 263).

defined mafic and felsic domains is strong evidence of two-liquid equilibrium.

Mafic phenocrysts locally appear to have settled as clots showing some grain-to-grain contact. This is compatible with operation of liquid immiscibility. My guess is that crystal settling operated on a small scale in the shonkinite and immiscibility operated on a larger scale during crystallization.

#### Petrology and Petrography of the Upper Lower Shonkinite

The lowest shonkinite grades into the upper lower shonkinite. Several differences make the division useful. In hand sample, the upper lower shonkinite is darker than the lowest shonkinite because it contains more mafic minerals. It tends to be more friable and weathered than the lower unit. Minerals visible with a hand lens include augite phenocrysts, orange olivine, biotite and a chalky mixture of zeolite and feldspar. The augite phenocrysts are larger than in the lower unit.

Thin-sections reveal the same minerals that appear in the lowest shonkinite. In addition, traces of sphene, aegirine-augite, and chlorite appear. Total mafic mineral content averages 55%, in contrast to 45% in the lowest shonkinite. Most olivine in the upper unit is heavily altered, rimmed by and converted to iddingsite and locally serpentine. Augite is more resorbed. Green mica locally rims biotite. Zeolites are more abundant than in the lower shonkinite. Separation into mafic and felsic patches resembles that in the lower shonkinite.

Mafic mineral content increases upward through the lower shonkinite of Round Butte laccolith as noted by Hurlbut and Griggs (1939) and is



consistent with Edmond's (1980) model of two-liquid equilibrium. As gravity-controlled separation proceeds, the laccolith crystallizes from the outside inward permitting immiscible separation to continue longer in the central part of the laccolith. More felsic material can separate from the parts that crystallize last, such as the upper unit of the lower shonkinite. This naturally leaves more mafic residual rock overlying earlier-crystallized, more felsic shonkinite.

Greater alteration of K-feldspar to zeolite and olivine to iddingsite and serpentine in the upper lower shonkinite can be explained several ways. If alteration is the result of late-magmatic processes, then it would accompany an increase in water content of the late-stage magma due to fractionation of the water into the magma with crystallization. It is doubtful that the magma at depth ever contained more than a few percent water. Mafic magmas are best considered to originate "dry," with some carbon dioxide present (Hyndman, 1983, page 105). Groundwater may have entered the magma from the groundwater reservoir before crystallization. Or, alteration may have followed crystallization as groundwater entered the laccolith. Shonkinite dikes near Round Butte generally show less zeolite alteration than the laccolith, suggesting that alteration in the laccolith is due to late magmatic water that accumulated in the magma as crystallization proceeded and not to post-magmatic processes, which probably would have affected the dikes and laccoliths to a similar degree.

#### Petrology and Petrography of the Lower Syenite

The lower syenite can be divided into two parts--medium- to coarse-

grained syenite and extremely coarse, extremely variably-textured syenitic pegmatite.

In hand specimen, the lower syenite is medium- to coarse- grained with 10 to 15% augite phenocrysts. It resembles the upper syenite except for the large size of the augite phenocrysts. Also visible are biotite flakes, K-feldspar grains, zeolite, and locally glassy grains of nepheline. Mafic phenocrysts are randomly distributed in a felsic matrix and rarely touch each other. Radial intergrowths of augite and zeolite commonly have straight boundaries that suggest a pseudomorphous origin, perhaps after nepheline. In thin section augite phenocrysts are rough, pitted and embayed. Separate resorbed or broken fragments of augite commonly appear in optical continuity. Green aegirine-augite rims most of the fragments and forms tiny grains in the groundmass. A few relict grains of olivine are devoid of crystal form, pitted, embayed, and rimmed with iddingsite. Flakes of biotite rim and contain most mafic remnants. Cumulate texture is not apparent.

Large four millimeter phenocrysts of fresh K-feldspar and, rarely, nepheline are typically in clots of three or four grains. These clots are in a fine groundmass of acicular K-feldspar, biotite, zeolite, glass and magnetite. Acicular feldspar grains are primarily-curved and radiate from numerous centers throughout the rock (Figure 8).

Magnetite appears as subhedral octahedra, full of inclusions that occupy so much space that less than half of the mineral within the crystal boundary is actually magnetite (Figure 8). The overall effect is of concurrent rapid growth of K-feldspar phenocrysts and magnetite

and destruction of augite followed by almost instantaneous solidification of the groundmass, probably at an eutectic point. Large K-feldspar crystals may have grown as the system moved down the liquidus surface (Figure 9).

Augite phenocrysts may have settled from the syenite unit to form the more mafic lower syenite, the "transition unit" of previous workers. Smaller syenitic segregations within the shonkinite show sharp, non-transitional boundaries (Figures 6 and 7). A transitional boundary between the main units of shonkinite and syenite may not be present. A syenite dike in the lower shonkinite indicates that partially liquid syenite once existed above solid shonkinite. Augite crystals could have settled from the liquid syenite if the viscosity and grain size were appropriate.

Thin sections of both upper and lower syenite indicate that the mean phenocryst length in the upper syenite is 4 millimeters. In the lower syenite this increases to 6.5 millimeters. Bottinga and Weill (1972) give viscosities of silicate melts at various temperatures. Compositions closely approximating syenite from Round Butte have an experimental viscosity of 1810 poise at 1300<sup>0</sup> C. Lower temperature would increase this value, while addition of water would decrease it. There is good evidence for water in the syenite at Round Butte during crystallization, for example extensive zeolitization of feldspar and extensive alteration of olivine to iddingsite.

Stokes' Law calculates rates of settling of spherical solids in a fluid medium as a function of grain size, density of fluid and solid

phases, and the viscosity.

$$V = \frac{2gr^2 (ds-dm)}{9u}$$

where V = settling velocity  
 g = acceleration of gravity  
 r = radius of settled grain  
 ds = density of solid phase  
 dm = density of magma  
 u = viscosity of magma

If  $r = 0.32$  centimeters,  $ds =$  density of augite =  $3.40$  g/cc (Troeger, 1979, page 72),  $dm =$  density of liquid syenite =  $(0.9) \times (\text{density of solid syenite}) = (0.9) \times (\text{density of orthoclase}) = 2.43$  g/cc, and  $u = 1810$  poise, then augite crystals would settle 10 meters per day. A drastic increase in magma viscosity due to falling temperature will decrease settling rates, but not beyond the realm of geologic possibility. Viscosity is inversely proportional to the logarithm of the temperature (Hyndman, 1983, page 143). A melt viscosity of 1,810,000 poise, 1000 times the value for the previous calculation corresponds to anhydrous syenite magma at  $900^{\circ}\text{C}$ . Augite crystals of the same size settle 3.6 meters per year in this magma. It is possible that augite crystals settled to produce the more-mafic lower syenite.

The lower syenite does not show cumulate textures as might be expected from a crystal settling mechanism perhaps because the mafic minerals content is so low. Random thin-sections through this rock may not show any grain-to-grain contact, even if some does exist. The possibility exists of differentiation in the syenite via secondary separation of immiscible liquids or some other mechanism.

Unfortunately exposures syenite are not good enough to show conclusive contact relationships. Vertical elongate patches of very fine-grained felsic material in the upper syenite appear to be late differentiates, perhaps through immiscible processes.

In hand specimen, the pegmatite is light-gray, syenitic with large two to three centimeter augite phenocrysts, typically in radial aggregates. Augite has a very rough surface texture. Biotite plates two to three millimeters across float in the groundmass. Fingerprint graphic intergrowths of augite and zeolite like in the lower syenite exist in greater abundance in the pegmatite. In a few places, the groundmass contains fine-grained asicular augite and biotite.

Thin-sections reveal that the pegmatite contains a few large embayed crystals of augite. These have dark green rims of aegirine-augite, which also occurs as needles in the groundmass. Biotite exists as a few embayed plates. Nearly 80% of the rock consists of a mixture of fine K-feldspar and zeolite.

#### Petrology and Petrography of the Upper Syenite

The upper syenite is nearly homogeneous. The syenite in segregations within the lower shonkinite unit is identical to that of the main wedge. They are both discussed here.

In hand specimen, the upper syenite is equigranular, light green-gray, speckled with a few mafic grains. Minerals seen with a hand lens include black augite and biotite, gray-green zeolite and creamy feldspar, plus scattered glassy nepheline crystals. Albite twins can be

seen on a few feldspar surfaces, so plagioclase is present though very minor.

In thin section, the syenite appears uniform throughout, including the segregations in shonkinite. Clots of large three to four millimeter K-feldspar phenocrysts swim in a groundmass of wildly acicular fine-grained feldspar and biotite (Figure 8). Typically the fine feldspar occurs in curved radial segregations scattered with small grains of aegirine-augite. Scattered ragged pieces of augite are in optical continuity. These have dark green aegirine-augite rims, even on broken surfaces, which suggests that the augite crystals began to dissolve before or during precipitation of aegirine-augite. Rare remnants of olivine are surrounded by iddingsite. Augite, olivine, and to a lesser degree biotite appear to have been disintegrating in the syenitic environment before crystallization. Magnetite is common, with the same skeletal texture noted in the lower syenite. A few grains of riebeckite exist in association with aegirine-augite (Figure 8).

The felsic immiscible differentiate probably contained appreciable mafic minerals. Once trapped in the felsic magma the mafic phenocrysts began to dissolve while the system travelled down the liquidus (Figure 9). Mafic mineral disintegration may have been halted by sudden eutectic crystallization of the syenitic magma, which may also be responsible for acicular habits of crystals in the groundmass.

#### Petrology and Petrography of the Upper Shonkinite

In hand sample, the upper shonkinite is a black and white speckled rock with medium-grained augite phenocrysts against a matrix of fine

feldspar and zeolite. Brownish altered olivine and brown biotite are scattered throughout the rock, which resembles the upper lower shonkinite.

In thin section, the rock also resembles the lower shonkinite. Modal analysis indicates about 33% mafic minerals in the upper shonkinite, somewhat less than the 45% in the lowest shonkinite. Felsic segregations are present in the groundmass between clots of predominantly mafic composition. Graphic intergrowths of K-feldspar and zeolite after nepheline occur in the felsic groundmass. Mafic minerals are embayed and riddled with late magmatic feldspar and biotite. Zeolite is bounded by straight lines in some places suggesting that it preferentially attacks certain minerals, perhaps nepheline. In other places zeolite is seen interfingering with unaltered K-feldspar.

The upper shonkinite probably approximates the composition of chilled parent magma. It is rather coarse grained and contains mafic and felsic domains in thin section. Apparently the upper shonkinite began to separate immiscibly before it solidified. Unfortunately erosion has removed the rest of the chill zone above the exposure. Mineralogical similarities between the upper shonkinite and the lowest shonkinite suggest a continuous envelope once enclosed the entire laccolith.

#### Petrology and Petrography of Dikes Near Round Butte

Dikes near Round Butte laccolith are mostly shonkinite, locally containing pseudoleucite. Buie (1941) states that the presence of

leucite or sanidine depends upon the rate of cooling of the dike, not on chemical differences between dikes. In hand sample, the shonkinite dikes are extremely dark, hard, and dense. They contain beautifully euhedral, prismatic augite phenocrysts, occasionally twinned with lesser trapezohedra of white pseudoleucite in a groundmass of olivine, fine K-feldspar, glass, hematite, apatite, and perhaps some analcime. In thin section, the rock is dominated by euhedral augite and lesser euhedral olivine phenocrysts in a groundmass of K-feldspar, zeolite, and brownish iddingsite. Iddingsite exists both as rims on olivine and as groundmass grains which appear to be pseudomorphs after olivine. Olivine in these rocks shows extensive alteration, but the feldspars are not heavily altered to zeolite.

One light-colored biotite-augite trachyte dike outcrops northwest of the laccolith. In hand specimen the rock is light gray with abundant sandstone xenoliths. Minerals seen with a hand lens include large biotite flakes, small augite prisms, and elongate K-feldspar grains which show strong parallel orientation. In thin section this rock is dominated by fine-grained feldspar and also contains oriented euhedral augite, biotite, magnetite, and apatite. Augite in this dike is much less zoned, has a better basal parting and a different color than augite in the shonkinite dikes. Contrasting augite properties indicate that the light-colored dike has a different source than the shonkinite dikes. I suspect this dike is associated with early latite dikes originating during the first phase of Highwood Mountain volcanism and intrusion (Buie, 1941).



### Chemistry of Round Butte Laccolith

Nine samples from Round Butte laccolith were analyzed for major element content by X-Ray Assay Laboratories in Toronto. One earlier analysis of syenite from Round Butte was also available (Pirsson, 1905) and is included here. Samples and their rock type, elevation, and location of samples are listed in Table 2.

Table 2  
Sample Number, Rock Type, Elevation and Location For Analyzed Samples.

<u>Sample Number</u>	<u>Rock Type</u>	<u>Elevation</u> (ft)	<u>Location</u>
2-1	Lower Shonkinite	4,400	North edge of laccolith
6-3	Lower Shonkinite	4,630	Central Ridge
3-1	Lower Shonkinite	4,700	South edge
3-6	Syenite	5,320	West edge of Syenite cliff
3-8A	Syenite	5,260	South edge of Syenite cliff
5-7B	Fine-grained Syenite	5,300	NE corner, syenite cliff
Pirsson, 1905	Syenite	?	?
1-6B	Upper Shonkinite	5,080	NE corner of laccolith
D-1A	Dike	4,300	East of laccolith
D-7	Dike	4,200	SW of laccolith

Weight percent of 11 elements of samples from Round Butte laccolith are in Table 3. Samples of mafic shonkinite are enriched in calcium, magnesium, iron, phosphorus and chromium. Elements enriched in the felsic syenite are aluminum, potassium, sodium, rubidium, strontium and zirconium. Elements equally present in both rocks are silicon,

TABLE 3 -- WHOLE-ROCK CHEMICAL DATA OF SAMPLES FROM ROUND BUTTE LACCOLITH.

	Lowest Shonkinite AL-2-1	Shonkinite AL-3-1	Shonkinite AL-6-3	Upper Shonkinite AL-1-6B		Syenite AL-3-8A		Pirsson (1905)		Dikes AL-D-1A	AL-D-7
SiO <sub>2</sub>	47.8	47.3	46.8	47.1	49.9	50.8	50.4	50.11	47.6	48.7	
TiO <sub>2</sub>	0.80	0.72	0.74	0.86	0.85	0.80	0.51	0.82	0.70	0.82	
Al <sub>2</sub> O <sub>3</sub>	12.0	10.4	9.44	11.4	16.6	18.4	18.8	17.13	12.3	13.3	
FeO & Fe <sub>2</sub> O <sub>3</sub>	9.18	9.27	9.71	10.0	7.61	7.11	6.42	7.01	8.98	9.06	
MnO	0.16	0.17	0.17	0.17	0.04	0.17	0.16	Trace	0.17	0.16	
MgO	8.48	10.5	11.5	8.58	2.83	1.70	1.23	2.47	8.21	6.92	
CaO	9.36	10.4	11.7	10.4	5.59	3.58	4.27	5.09	9.19	9.00	
Na <sub>2</sub> O	3.21	2.32	2.65	2.74	2.90	5.60	3.25	3.72	2.72	2.61	
K <sub>2</sub> O	4.45	4.64	3.15	4.26	7.91	6.06	7.59	7.47	4.77	4.06	
P <sub>2</sub> O <sub>5</sub>	1.02	1.07	1.14	1.24	0.61	0.34	0.21	0.67	0.97	0.81	
Cr <sub>2</sub> O <sub>3</sub>	0.03	0.04	0.04	0.03	--	--	--	--	0.02	0.02	
LOI	2.16	2.16	2.00	2.47	3.62	3.85	5.85	4.47	2.47	2.93	
Total	98.8	99.1	99.2	99.4	98.8	98.8	99.0	99.0	98.4	99.6	
Rb (ppm)	80	120	60	60	180	80	280	--	100	120	
Sr (ppm)	1360	1100	1040	1240	1880	2690	1980	--	1920	1480	
Zr (ppm)	140	120	130	150	210	300	340	--	160	140	

manganese and titanium.

It is surprising that silicon is equally distributed throughout the shonkinite and syenite. Higher silicon is expected in the felsic syenite, where polymerization is greater than in the mafic shonkinite. If aluminum is also considered, then the syenite has the greater potential for polymerization, since the sum of silicon and aluminum is greater in the syenite than in the shonkinite.

Highly polymerized alkaline silicate melts with added high field strength cations form immiscible systems, and the field of immiscibility is related to coexistence of branched and unbranched silicates (Hess, 1971). Partitioning of elements between two coexisting magmas has been documented experimentally (see Freestone, 1973; Watson, 1976; Ryerson and Hess, 1978; Freestone and Powell, 1983). Cations with a high charge to radius ratio (field strength) such as calcium, chromium, titanium, manganese, and strontium theoretically partition into the more mafic melt, because it contains more non-bridging oxygen than the felsic melt. Non-bridging oxygen are those which do not polymerize.

High field strength cations form ligands with non-bridging oxygen, and oxygen ions surrounding the cation shield it from electrostatic repulsion with neighboring cations. This shielding is called "anionic screening," and it helps to stabilize high field strength cations in the basic melt (Ryerson and Hess, 1978). These cations are unable to substitute for silicon in tetrahedral coordination with oxygen (Watson, 1976) because they do not meet the radius ratio requirements of tetrahedral locations. This effect is greater in the felsic melt than

in the basic melt because there are more tetrahedral sites in the felsic melt. Also, the highly-polymerized felsic melt has fewer non-bridging oxygen ions than the mafic melt, so the stability of high field strength cations in this melt is decreased due to cation-cation repulsion. These cations have difficulty finding suitable sites in the felsic melt and are more easily accepted into a basic melt.

Cations of low charge density such as potassium and sodium are found in the highly polymerized felsic melt in experimental systems. This is due to substitution of +3 aluminum for +4 silicon in silica tetrahedra creating a charge imbalance. Addition of cations with a +1 valance charge satisfies this charge imbalance (Ryerson and Hess, 1978).

Phosphorus is strongly partitioned into the mafic shonkinite at Round Butte laccolith. Distribution of phosphorus between mafic and felsic magmas has been suggested as an indicator of the process that caused differentiation. Watson (1976) and Visser and Koster Van Groos (1979b) document enrichment of phosphorus in mafic melts as a result of immiscible processes. The mechanism of partitioning remains ambiguous. Ryerson and Hess (1978) state that phosphorus exists in silicate melts as phosphate ion, not as isolated +5 phosphorus ions. The very large amount of energy required to ionize the phosphorus atom five times is not likely to be found in silicate magmas. The phosphate group may form complexes with metallic ions in silicate melts. Enthalpy of formation of such complexes appears to be favorable. Partitioning of phosphorus into mafic magmas during immiscible processes is probably due to a greater

number of suitable metal ions in the more mafic melt.

Anderson and Greenland (1969) state that phosphorus is enriched in the residual liquid when fractional crystallization occurs. Once a phosphorus mineral such as apatite begins to crystallize though, phosphorus may become depleted in the residual liquid. In this case the distribution of phosphorus between mafic and felsic rocks may not be useful in determining the mode of differentiation of a specific rock suite (Ryerson and Hess, 1978). Thin sections from Round Butte indicate that apatite crystallized early (See page 21), indicating that phosphorus depletion in the syenite is not due to fractionation into the felsic liquid and removal by late crystallization of apatite. Early partitioning of phosphorus into the mafic shonkinite is better explained by liquid immiscibility theory than by fractional crystallization theory.

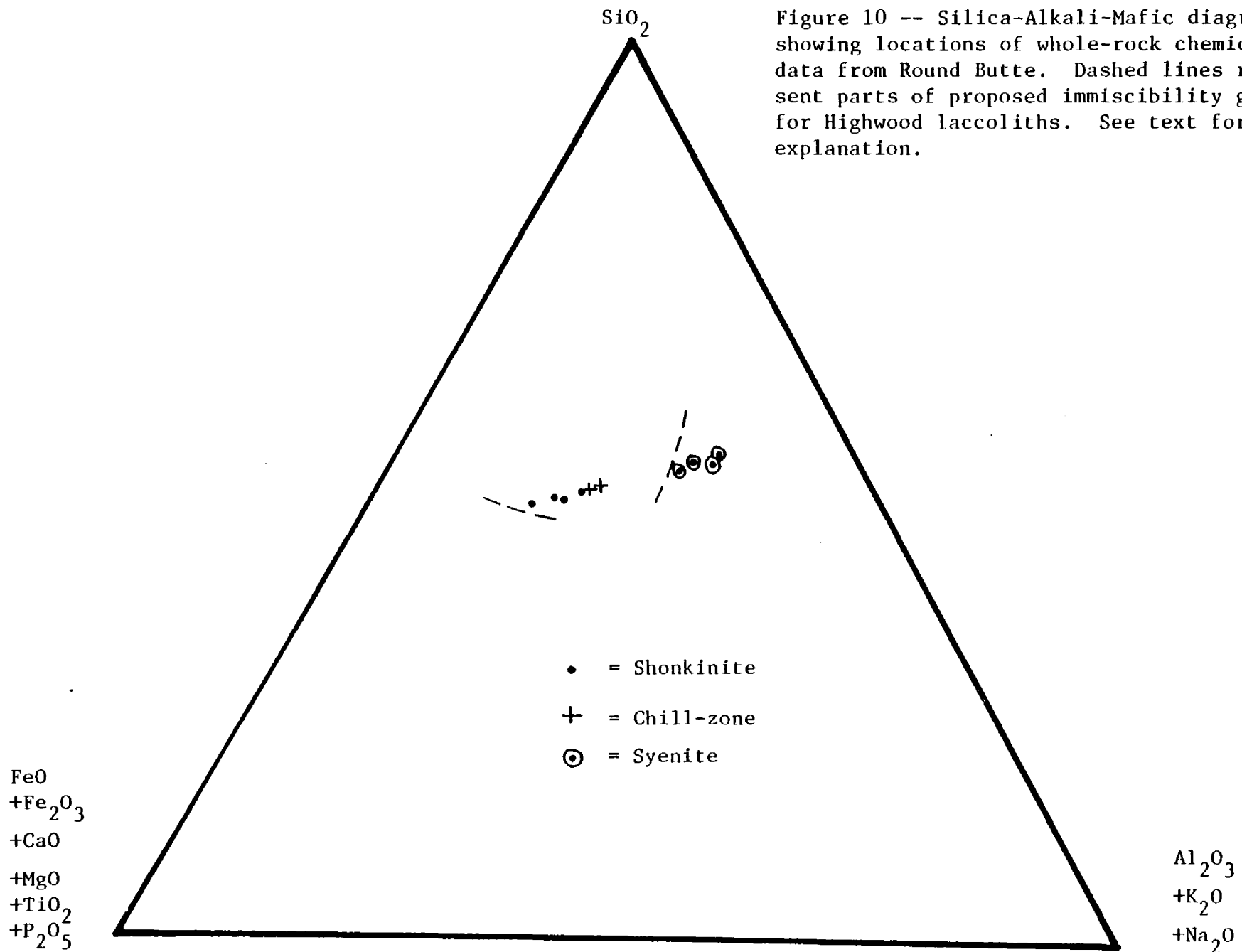
Fractional crystallization and crystal settling may produce abrupt changes in sequences of rock. If enough time elapses while the rock is liquid, all the dense crystals may settle to the bottom of the laccolith. However, fractionation and crystal settling in geologic settings usually produce gradational sequences of both rocks and solid-solution minerals within those rocks (See Hyndman, 1983, pages 170, 288-289). Inherent in the application of immiscible processes to rock bodies are rapid changes in rock type and composition without gradation between the mafic and felsic units. Differences in the composition of shonkinite and syenite samples reflecting their domainal nature in the field is expected. A well-defined compositional gap between shonkinite

and syenite samples on the Silica-Alkali-Mafic diagram (Figure 10) suggests a discontinuous processes like liquid immiscibility.

Data from laccoliths in the Montana alkalic province show some agreement with experimental trace-element partitioning studies, for example, the Shonkin Sag laccolith (Edmond, 1980), Square Butte laccolith (Kendrick, 1980), and Box Elder laccolith (Kuhn, 1983). It must be kept in mind that experimental systems only approximate behavior of natural systems.

Rocks of Round Butte laccolith are plotted on the Silica-Alkali-Mafic ternary diagram below (Figure 10). Shonkinite samples group on one side of the plot, syenite samples on the other side, and chilled samples fall between. This arrangement suggests derivation of mafic and felsic magmas from the chilled samples. Locations of coexisting shonkinite and syenite on this diagram may represent the end points of tie-lines that spanned an immiscibility gap. Sequentially longer tie-lines may represent either longer periods of crystallization or expansion of the field of immiscibility with decreasing temperature or both. A longer period of crystallization allows magmatic immiscibility to operate longer. This permits more complete separation of syenite and shonkinite, hence greater separation on figure 10. Expansion of the immiscibility field with decreasing temperature would produce more differentiated magmas. The spread between samples of the same rock type on Figure 10 becomes understandable if we note that the samples that plot farthest from the chill-zone samples are closest to the center of the laccolith, where crystallization occurred last and liquid

Figure 10 -- Silica-Alkali-Mafic diagram showing locations of whole-rock chemical data from Round Butte. Dashed lines represent parts of proposed immiscibility gap for Highwood laccoliths. See text for explanation.



immiscibility acted for the longest period. The dashed segments on Figure 10 represent parts of a proposed immiscibility gap that developed during crystallization at Round Butte laccolith (see Page 40).

Syenites from Round Butte plot, in order of increased differentiation from chill zone samples, 3-6, Pirsson's (1905) sample, 3-8A, and 5-7B. Sample 3-6 was taken at higher elevation than sample 3-8A. A longer period of crystallization allows differentiation to more fully affect syenite at lower elevation close to the center of the laccolith, perhaps by allowing more mafic phenocrysts to settle out. Pirsson's sample plots between the two samples discussed above, so it probably came from an intermediate location. Fine-grained felsic segregations (Sample 5-7B) within the upper syenite plot to the extreme right side of the syenite domain on figure 10. These segregations represent the extreme differentiate of the syenite. Similarities in field occurrence between these segregations and the syenite segregations in the lower shonkinite suggest that both are the result of immiscible processes. A later period of immiscibility may have worked in the syenite, in which case characteristic trace-element partitioning patterns should be observed. Phosphorous is depleted in the fine-grained phase relative to the syenite, suggesting immiscible partitioning into the medium-grained syenite. Iron and magnesium are also slightly depleted in the fine-grained phase. Other elements appear randomly distributed between the two phases.

In order of increasing differentiation from chill samples, shonkinites plot in the order 2-1, 1-6B, 3-1, 6-3. Sample 2-1 is the



lowest exposed shonkinite, which would be expected to show little differentiation since it crystallized quickly. Sample 1-6B is upper shonkinite. It also shows minor differentiation due to rapid crystallization. Minor immiscible separation in the upper shonkinite as shown by chemical data is further supported by petrographic evidence (see page 30). Sample 3-1 is close to the southern edge of the laccolith; it shows some differentiation but not as much as if it were closer to the center of the laccolith. Sample 6-3 is taken from the center of the laccolith and shows the most differentiation, as might be expected since it remained liquid longest.

Syenite compositions should plot at the edge of an immiscibility gap because they are pure differentiate from the shonkinite. Shonkinite compositions should fall within the field of immiscibility and progressively approach the field boundary with increased differentiation, because the shonkinite contains unseparated syenite. The points on Figures 10 and 11 do not fall on or within the boundaries of an experimental immiscibility field developed in the potassium-iron-aluminum-silica system (Visser and Koster Van Groos, 1979a). Addition of phosphorus and titanium to experimental alkaline magma enlarges the immiscibility field (Freestone, 1978). Part of this enlarged field is shown on Figure 11. It more closely approximates the immiscibility gap that existed during crystallization of Round Butte laccolith. The dashed segments on Figures 10 and 11 represent part of this natural gap. Orientation of the dashed segments is similar to that of Freestone's (1978) boundaries. The segments were constructed so that relationships

41

between phase boundaries and data points were consistent in both the experimental and the natural systems.

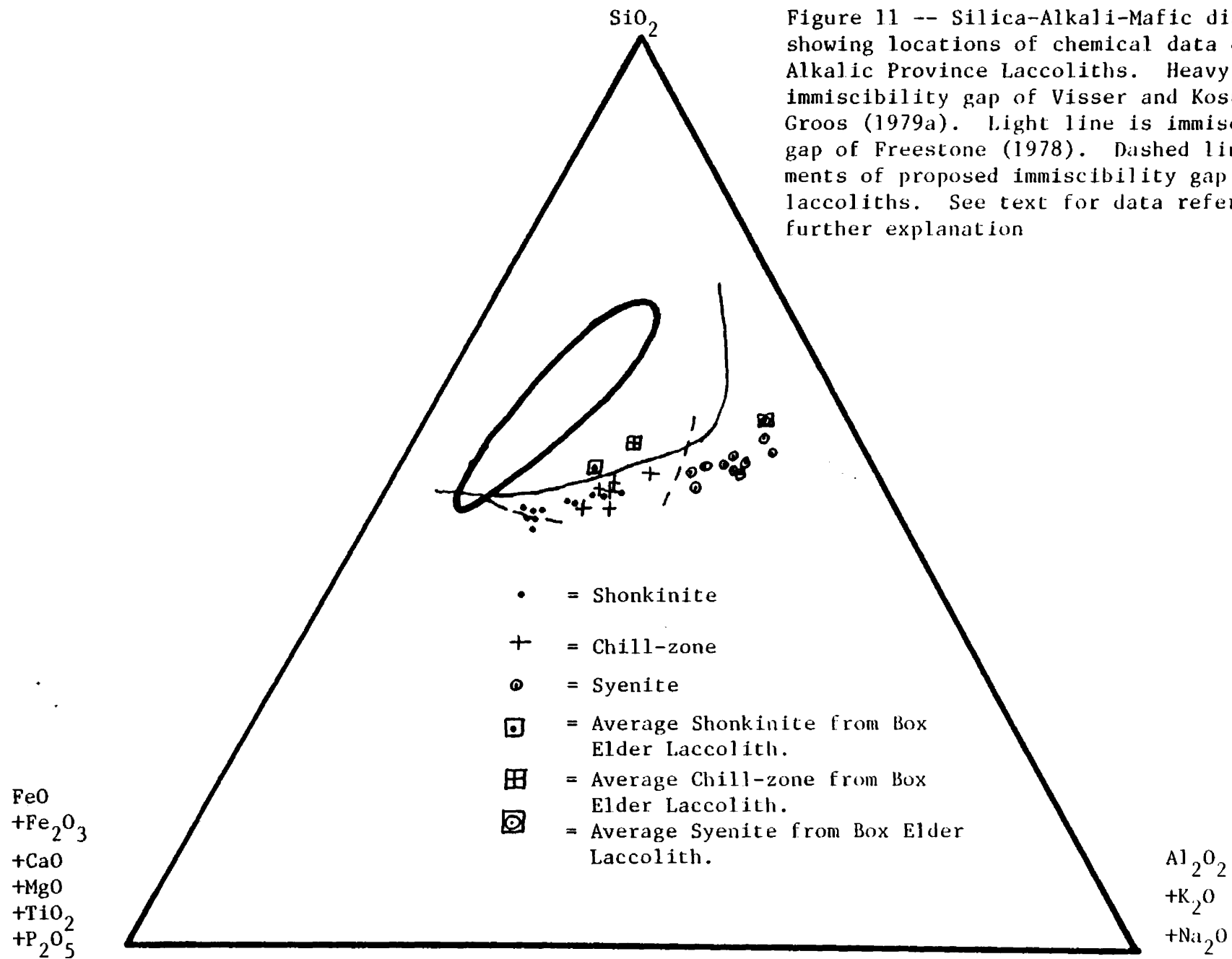
Differences between Freestone's (1978) experimental field and the field constructed for Round Butte may have several causes. The experimental system included six components, while Figure 11 plots sample composition based on nine components. Addition of components to the experimental system may shift the position of the field of immiscibility. The experimental system does not contain water. Water pressure in magma increases oxygen fugacity, resulting in increased compositional range of immiscibility and divergence of the compositions of the unmixed liquid pairs (Naslund, 1983). Philpotts (1976) plots samples from the Monteregian Hills of Quebec on a diagram similar to figure 11. The samples are interpreted as immiscible pairs of mafic and felsic rock, and their locations on the Silica-Alkali-Mafic diagram closely correspond to plots of samples from the Highwood Mountain laccoliths.

Chill-zone samples plot between the shonkinite and syenite, but closer to the shonkinite. Shonkinite is closer in chemical composition to the parent magma than syenite, so syenite is the more extreme differentiate. More parent magma is needed to produce a given volume of syenite than an equal volume of shonkinite. Since a fixed volume of magma formed Round Butte, more shonkinite would be produced than syenite. This is seen in the field, where the volume of syenite is at most 15% of the volume of shonkinite, because no basal shonkinite contact is exposed.

Figure 11 plots the compositions of rocks from the Shonkin Sag laccolith (Osborne and Roberts, 1931; Hurlbut and Griggs, 1939; Hyndman, unpublished data, 1984), Square Butte laccolith (Pirsson, 1905; Hurlbut and Griggs, 1939; Hyndman, unpublished data, 1984), Round Butte laccolith (Pirsson, 1905; Liptak, this report), and from the Box Elder laccolith in the Bearpaw Mountains (Kuhn, 1983). In every laccolith, shonkinites plot on the mafic side of the diagram, the syenites on the felsic side, and chilled samples fall between. All of these laccoliths are thought to have formed by immiscible processes (Kendrick, 1980; Edmond, 1980; Kuhn, 1983; Liptak, this report). This pattern is probably characteristic of differentiation by immiscible mechanisms.

Hurlbut and Griggs' (1939) analysis of the lower syenite of Shonkin Sag laccolith plots near the upper syenite. Its position toward the mafic corner of the diagram relative to most other syenite samples indicates enrichment of mafic minerals in the lower syenite through crystal settling. Coincidence of plots of shonkinite, upper syenite and chill zone samples from the Shonkin Sag and Round Butte laccoliths suggests that the composition of lower syenite of Round Butte is chemically comparable to that of Shonkin Sag, in which case the conclusions above should hold for Round Butte also.

More striking is the tight clustering of points from laccoliths in the Highwood Mountains, which plot on a tight arc. Evidently all came from the same parent magma in the eastern Highwood Mountains. Also striking is the fact that rocks of the Box Elder laccolith plot extremely close to the Highwood laccoliths, despite a 108 kilometer



separation between the Bearpaw and Highwood Mountains. This suggests that the magmas that formed both the Highwood and Bearpaw laccoliths are differentiates from the same primary source.

### CONCLUSION

Round Butte is a potassium-rich alkalic laccolith genetically associated with other alkalic laccoliths in the Highwood area, notably the Shonkin Sag and Square Butte laccoliths. It contains basal shonkinite overlain by a wedge-shaped body of syenite, which is in turn overlain by a small remnant lens of upper shonkinite. The lower shonkinite becomes more mafic upward and the syenite coarsens downward. A combination of field, petrographic, and chemical evidence points toward liquid immiscibility as the dominant mechanism of differentiation in Round Butte. Crystal settling may have worked on a minor scale in the shonkinite during immiscible separation. Small syenite patches within the lower shonkinite appear to be immiscible segregations trapped upon crystallization of the shonkinite.

A dike of coarse syenite within the lower shonkinite shows that shonkinite crystallized before the syenite, leaving a lens of partially liquid syenite overlying solid shonkinite. Mafic crystals from the syenite may have settled, forming a basal syenite, more mafic than the upper syenite. This unit had been previously interpreted as a transition unit (Hurlbut and Griggs, 1939). Syenite pegmatite samples found in the talus on Round Butte indicate that pegmatite exists in the lower syenite, but it is unexposed.

Chemical analysis of syenite and shonkinite from Round Butte show two distinct compositional domains on Silica-Alkali-Mafic diagrams. Shonkinites plot together towards the mafic corner, the syenites plot together toward the alkalic corner and chilled dike samples fall on a

line between. The compositional gap between the two domains further supports the argument that the mechanism of differentiation on Round Butte was immiscible separation of shonkinite magma. Coincidence of plots of samples from the Square Butte and Shonkin Sag laccoliths with those of Round Butte strongly suggests a common parent magma for the three laccoliths.

# BIBLIOGRAPHY

- Anderson, A.T., and Greenland, L.P., 1969, "Phosphorus Fractionation Diagram as a Quantitative Indicator of Crystallization Differentiation of Basaltic Liquids," *Geochimica et Cosmochimica Acta*, Vol. 33, pp. 493-505.
- Barksdale, J.D., 1937, "The Shonkin Sag Laccolith," *American Journal of Science*, Volume 33, pp. 321-359.
- \_\_\_\_\_, 1951, "The Shonkin Sag Laccolith Revisited," Abstract, *American Mineralogist*, Volume 36, page 310.
- Bottinga, Y., and Weill, D.F., 1972, "The Viscosity of Magmatic Silicate Liquids: A Model for Calculation," *American Journal of Science*, Vol. 272, pp. 438-475.
- Bowen, N.L., 1928, "The Evolution of the Igneous Rocks," Princeton, Princeton University Press, 334 pages.
- Buie, B.F., 1939, "Dikes and Related Intrusives of the Highwood Mountain Area, Montana," Ph.D. Dissertation, Harvard University, 126 pages.
- \_\_\_\_\_, 1941, "Igneous Rocks of the Highwood Mountains; Part III Dikes and Related Intrusives," *Geological Society of America Bulletin*, Vol. 52, pp. 1753-1808.
- Edmond, C.L., 1980, "Magma Immiscibility in the Shonkin Sag Laccolith, Highwood Mountains, Central Montana, M.S. Thesis University of Montana, 97 pages.
- Freestone, I.C., 1978, "Liquid Immiscibility in Alkaline-rich Magmas," *Chemical Geology*, Vol. 23, pp. 115-123.
- \_\_\_\_\_, and Powell, R., 1983, "The Low Temperature Field of Liquid Immiscibility in the System  $K_2O-Al_2O_3-FeO-SiO_2$  With Special Reference to the Join Fay-Leu-Si," *Contributions to Mineralogy and Petrology*, Vol. 82, pp. 291-299.
- Hess, P.C., 1971, "Polymer Model of Silicate Melts," *Geochimica et Cosmochimica Acta*, Vol. 35, pp. 289-306.
- Hurlbut, C.S., and Griggs, D.T., 1939, "Igneous Rocks of the Highwood Mountains, Montana, Part 1, The Laccoliths," *Geological Society of America Bulletin*, Vol. 50, No. 7, pp. 1032-1112.
- Hyndman, D.W., 1983, "Petrology of Igneous and Metamorphic Rocks," Second Edition, In Press.



- 
- \_\_\_\_\_, and Alt, D., 1983, "Emplacement of Alkalic Intrusives, Central Montana," Geological Society of America, Abstracts with Programs, 36th Annual Meeting, Rocky Mountain Section, May 2-4, 1983, page 420.
- Kendrick, G.D., 1980, "Magma Immiscibility in the Square Butte Laccolith of Central Montana," M.S. Thesis, University of Montana, 90 pages.
- Kendrick, G.D., and Edmond, C.L., 1981, "Magma Immiscibility in the Shonkin Sag and Square Butte Laccoliths," *Geology*, Vol. 9, pp. 615-619.
- Kuhn, P.W., 1983, "Magma Immiscibility in the Box Elder Laccolith of North-Central Montana, M.S. Thesis, University of Montana, 86 pages.
- Larsen, E.S., 1941, "Igneous Rocks of the Highwood Mountains, Montana, Part II: The Extrusive Rocks," Geological Society of America Bulletin, Vol. 52, pp. 1733-1752.
- Morse, S.A., 1980, "Basalts and Phase Diagrams," New York, Springer Verlag, 493 pages.
- Naslund, H.R., 1983, "The Effect of Oxygen Fugacity on Liquid Immiscibility in Iron-bearing Silicate Melts," *American Journal of Science*, Vol. 283, pp. 1034-1059.
- Osborne, E.F., and Roberts, E.J., 1931, "Differentiation in the Shonkin Sag Laccolith, Montana," *American Journal of Science* Vol. 22, pp. 331-353.
- Phillips, W.J. 1973, "Interpretation of Crystalline Spheroidal Structures in Igneous Rocks," *Lithos*, Vol. 6, pp. 235-244.
- Philpotts, A.R., 1976, "Silicate Liquid Immiscibility: Its Probable Extent and Petrogenetic Significance," *American Journal of Science*, Vol. 276, pp. 1147-1177.
- Pirsson, L.V., 1905, "Petrography and Geology of the Igneous Rocks of the Highwood Mountains, Montana," U.S. Geological Survey Bulletin 237, 208 pages.
- Ryerson, F.J., and Hess, P.C., 1978, "Implications of Liquid-Liquid Distribution Coefficients to Mineral-Liquid Partitioning," *Geochimica et Cosmochimica Acta*, Vol. 42, pp. 921-932.
- Troeger, W.E., 1979, "Optical Determination of Rock-Forming Minerals"; E. Schweizerbart'sche Verlagsbuchhandlung, 188 pages.

- Visser, W., and Koster Van Groos, A.F., 1979a, "Phase Relations in the System  $K_2O-FeO-Al_2O_3-SiO_2$  at One Atmosphere with Special Emphasis on Low Temperature Liquid Immiscibility," American Journal of Science, Vol 279, pp. 70-91.
- 
- \_\_\_\_\_, 1979b, "Effects of  $P_2O_5$  and  $TiO_2$  on Liquid-Liquid Equilibria in the System  $K_2O-FeO-Al_2O_3-SiO_2$ ," American Journal of Science, Vol. 279, pp. 970-988.
- 
- \_\_\_\_\_, 1979c, "Effect of Pressure on Liquid Immiscibility in the System  $K_2O-FeO-Al_2O_3-SiO_2-P_2O_5$ ," American Journal of Science, Vol. 279, pp. 1160-1175.
- Wallace, S.R., 1953, "The Petrology of the Judith Mountains, Fergus County, Montana," Ph.D. Dissertation, University of Michigan, pp. 117-123.
- Watson, E.B., 1976, "Two-Liquid Partition Coefficients: Experimental Data and Geochemical Implications," Contributions to Mineralogy and Petrology, Vol. 56, pp. 119-134.
- Weed, W.H., and Pirsson, L.V., 1895, "Highwood Mountains of Montana," Geological Society of America Bulletin, Vol. 6, pp. 389-422.
- Witkind, I.J., 1965, "Relation of Laccolithic Intrusion to Faulting in the Northern Part of the Barker Quadrangle, Little Belt Mountains, Montana," U.S. Geological Survey Profesional Paper 525-C, pp. 20-24.